

GLOBAL CLUSTER SYSTEMS AS DISTANCE INDICATORS: METALLICITY EFFECTS ON THE LUMINOSITY FUNCTION

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ABSTRACT

We investigate the universality of the globular cluster luminosity function (GCLF) and the use of this function as an extragalactic distance indicator. Previous studies have found an offset between GCLF distances and those obtained with other techniques. We show that this offset can be understood in terms of a metallicity effect. Specifically, the globular cluster systems used in distance scale studies have traditionally been those around elliptical galaxies. These systems have higher mean metallicities than the Milky Way globular cluster system. Consequently, the peak of the GCLF in the systems around ellipticals is significantly fainter in B and V than the GCLF peak in the Milky Way. We calculate the shift in the peak of the GCLF relative to the Milky Way globulars in B , V , R , I and J for a range of globular cluster metallicities. Applying these corrections, we find good agreement between GCLF distances and those obtained using the surface brightness fluctuations method. The similarity between metallicity-corrected GCLFs suggests that the underlying mass function of globular cluster systems is remarkably constant from one galaxy to another. Our results allow the GCLF to be employed as an improved distance indicator.

1. INTRODUCTION

The use of globular clusters as extragalactic distance indicators has been reviewed in detail by Jacoby et al. (1992). The principal technique exploits the roughly Gaussian shape of the globular cluster luminosity function (GCLF), defined as the relative number of globular clusters as a function of magnitude (cf. Hanes & Whittaker 1987; Harris 1988; Harris et al. 1991). Such a distribution can be characterized by just two parameters: the dispersion σ and the peak M_0 . It is the GCLF peak that is used as a standard candle.

Clearly, the GCLF technique is only effective if the value of M_0 is constant or varies in a predictable manner from one galaxy to another. The lack of a generally accepted model of globular cluster formation means that there is no firm physical basis for supposing this to be true, although there is no shortage of suggestions as to why this might be the case (e.g. Fall & Rees 1985; Morgan & Lake 1989; Murray & Lin 1989; Ashman 1990; Larson 1990; Ashman & Zepf 1992; Harris & Pudritz 1994). The primary evidence that the GCLF peak is constant is empirical. For instance, the globular cluster systems of several Virgo ellipticals have GCLF peaks that vary by less than 0.2 magnitudes (van den Bergh et al. 1985; Harris et al. 1991; Secker & Harris 1993; Ajhar, Blakeslee & Tonry 1994).

While current results are generally encouraging, there are two areas of concern. The first is the claim that there might be an offset between the GCLF peaks in the Milky Way and M31 (Secker 1992; Reed et al. 1994). Since these globular cluster systems have the most complete luminosity functions, a difference between their peaks is worrying. The second potential problem was summarized neatly by Jacoby et al. (1992). These authors noted that the GCLF technique is more accurate than its error estimates, but that it yields distances that are offset by 13% relative to those obtained using the surface brightness fluctuations method. The sense of this offset requires that the GCLF peak in the observed elliptical galaxies is about 0.25 magnitudes fainter (in B) than the peak in the Milky Way (see also Fleming et al. 1995).

Formation models that attempt to explain the apparent universality of the GCLF typi-

cally predict a mass function or characteristic globular cluster mass. Given the uncertainties in the models, it is only sensible to regard the mass and luminosity functions as having the same form, by tacitly assuming that the mass-to-light ratio of all globular clusters is the same. However, it is equally apparent that systematic variations in mass-to-light ratio between globular cluster systems will result in different GCLFs, even if the underlying mass functions are identical. Such variations can be produced by differences in the age and metallicity of globular cluster systems.

The main purpose of this paper is to investigate the effects of variations in the mean metallicity of globular cluster systems on the GCLF. Jacoby et al. (1992) mentioned that this effect might produce around 0.1 magnitudes of scatter in the GCLF peak from galaxy to galaxy. However, the galaxies for which GCLF distances have been obtained are almost exclusively ellipticals which are known to have globular cluster systems with higher mean metallicities than the Milky Way and M31 systems (e.g. Harris 1991; Brodie & Huchra 1991; Zepf, Ashman & Geisler 1995). We therefore argue that current distance determinations using the GCLF suffer from a systematic bias and not simply a scatter resulting from metallicity-induced variations in the GCLF peak.

Using Worthey’s (1994) population synthesis models, we calculate the shift in the GCLF peak due to metallicity variations. We assume that the mass function of globular cluster systems is universal and convolve this mass function with metallicity distributions with a range of mean metallicities. We find that, for realistic metallicities, the shift in the GCLF peak relative to that of the Milky Way globulars can significantly exceed the 0.1 magnitudes estimated by Jacoby et al. (1992). Most importantly, we find that this metallicity effect naturally explains the 13% offset between GCLF distances and those obtained using the surface brightness fluctuations method. This suggests that, in principle, the GCLF may be used successfully as an accurate distance indicator.

The plan of the paper is as follows. In Section 2, we analyze the GCLFs of the Milky Way and M31 and find no statistically significant difference between the peaks of their GCLFs. We

also calculate the underlying mass functions of the two globular cluster systems. In Section 3 we calculate the shifts in the GCLF in B , V , R , I and J for a range of metallicities. We discuss the effect of this peak shift on distance estimates in Section 4. We show that accounting for this metallicity effect brings the GCLF distance scale in line with distances obtained using surface brightness fluctuations. We also show that our results favor a universal globular cluster mass function. Finally, in Section 5, we discuss directions for future work in this area and present our conclusions.

2. THE MILKY WAY AND M31

Recent work has suggested the possibility of an offset between the GCLF peak in the Milky Way and M31 (Secker 1992; Reed et al. 1994). Such an offset would undermine the use of the GCLF peak as a standard candle. We therefore study the V -band GCLFs of these systems in detail to establish whether a significant difference is present.

The Milky Way data come from the McMaster catalogue (Harris 1994) and consist of 122 globular clusters with V -band luminosities and spectroscopic metallicities. The metallicities are used in Section 2.2 below to convert the luminosity function into a mass function. (Limiting the dataset in this way excludes twelve clusters with V -band luminosities. The inclusion of these objects slightly reduces the peak value but the 90% confidence intervals are virtually unchanged.) Data for the M31 globular cluster system are taken from Reed et al. (1994). To convert to absolute magnitudes, we follow these authors in using an M31 distance modulus of $(m - M)_V = 24.6$, which assumes a reddening of $E(B - V) = 0.11$. Histograms of the V -band GCLFs for the Milky Way and M31 are presented in Figure 1.

A preliminary statistical analysis of the 122 Milky Way globular clusters reveals that the five faintest objects are more than 3σ from the mean of the distribution, assuming that the parent distribution is Gaussian. The traditional technique of employing the peak of the GCLF as a distance indicator assumes such a distribution. Since inclusion of the five faint clusters produces a highly non-Gaussian distribution, they are excluded from the subsequent analysis. From a practical point of view, these objects are so faint ($M_V \geq -3.30$) that they

would not be detected in observations of extragalactic globular cluster systems. Thus we restrict our attention to the remaining 117 Milky Way globular clusters.

It is worth noting that the use of the GCLF peak as a standard candle is not dependent on fitting a particular functional form to the GCLF. All that is required is a reproduceable method of identifying the peak (mode) of the GCLF in different datasets. Thus we do not ascribe any physical importance to the Gaussian form and use it only as a convenient method of determining a peak value. We return to this point in Section 2.1.

We analyse the Milky Way and M31 GCLFs using the ROSTAT statistics package (Beers et al. 1990; Bird & Beers 1993). Our results are summarized in Table 1. The peak value M_{V0} and dispersion σ for the two V -band GCLFs assume that the parent distributions are Gaussian. In other words, these quantities are the usual peak and dispersion quoted in GCLF studies. Table 1 also gives the robust biweight estimators of location and scale C_{BI} and S_{BI} which require no assumption about the parent distribution. We include the bootstrapped 90% confidence limits on both M_{V0} and C_{BI} . In the case of the Milky Way, the classical estimators give $M_{V0} = -7.33$ and $\sigma = 1.23$ in V -band, and $M_{B0} = -6.50$ and $\sigma = 1.13$ in B -band.

Our primary result is that there is no statistically significant difference between the GCLF peaks in the Milky Way and M31. This finding is supported by a two-distribution KS test that indicates the distributions are not significantly different. Table 1 shows that the 90% confidence limits on M_{V0} for the Milky Way and M31 GCLFs overlap. We find, like previous authors (e.g. Reed et al. 1994), that the M31 peak is brighter, but the difference is not statistically significant. In fact, if we assume that the peaks of the parent GCLFs are indistinguishable and that the distributions are Gaussian, the finite number of datapoints N inevitably produces an uncertainty in the mean of σ/\sqrt{N} . Using the values in Table 1 this corresponds to 0.11 mag for both the Milky Way and M31. The true uncertainty is larger than this value because the two distributions are somewhat non-Gaussian.

Table 1 also gives the skewness of the two distributions, along with the corresponding

P -values.¹ Both the distributions are skew, rejecting the hypothesis that the parent distribution is Gaussian. (For M31 the rejection is only marginally significant.) Interestingly, the distributions are skew in the opposite sense. This is reflected in the result that the robust estimator of location, C_{BI} , is brighter than the Gaussian peak M_{V0} in the case of the Milky Way distribution, but fainter than M_{V0} in M31. One other striking aspect about the results in Table 1 is that the dispersion (both the Gaussian and robust measures) is significantly higher for the Milky Way than M31.

2.1 Differences in the GCLFs

While the similarity in M_{V0} of the M31 and Milky Way distributions is encouraging for the GCLF distance estimation method, the differences in the shape and dispersion of the two GCLFs require further comment.

The dispersions of the GCLFs of the Milky Way and M31 quoted above and in Table 1 assume that the GCLFs are complete. There is some question whether this is the case in M31, since there are no globular clusters in the dataset fainter than $M_V = -5.5$, despite the presence of such low luminosity globulars in the Milky Way. The addition of such clusters to the M31 dataset would increase the dispersion of the GCLF and move the peak to fainter magnitudes. Since we cannot reasonably “add in” clusters to the M31 GCLF, we instead truncate the Milky Way GCLF, removing clusters fainter than $M_V = -5.5$. Applying ROSTAT to this truncated dataset we obtain $M_{V0} = -7.61$ and $\sigma = 0.95$ (the robust estimators yield $C_{BI} = -7.57$ and $S_{BI} = 0.97$). The peak of the Gaussian fit is marginally *brighter* than the M31 GCLF and the dispersion is *lower*. This supports the view that the dispersion in the M31 GCLF has been underestimated due to a non-detection of faint globulars and that M_{V0} has been pushed to a brighter value by the same effect.

¹Since the magnitude system assigns increasingly negative numbers to brighter objects, the skewness of a distribution of magnitudes has the opposite sign to the same dataset presented in terms of the logarithm of luminosity. We have therefore quoted the negative of the value of the skewness returned by ROSTAT. This ensures consistency between the skewness quoted for the GCLFs and the corresponding mass functions described in Section 2.2 below.

The remaining issue is whether the GCLF is Gaussian. Recall that we have culled five faint objects from the Milky Way dataset and that the remaining 117 points constitute a skewed distribution. Thus the central question is whether it is justifiable to fit a Gaussian to GCLFs when using them as distance indicators. An important consideration here is that in galaxies beyond M31, GCLFs are rarely observed much beyond M_{V0} . Thus in practice the best-fitting Gaussian to a GCLF is based on the brightest 50% or so of the distribution. Provided the skewness is being driven by faint clusters, the non-Gaussian nature of the Milky Way GCLF is not a concern when using the GCLF peak as a standard candle. We will give a full discussion of this topic and methods of fitting Gaussians to incomplete GCLFs in a future paper.

As an alternative to the Gaussian, Secker (1992) has suggested the use of the t_5 distribution, which he shows provides a better fit to several GCLFs. We feel that an equally valid approach is to use a Gaussian model but to use a 3σ clip to remove outliers. The real problem is that both the Gaussian and the t_5 distributions are symmetric, whereas the Milky Way GCLF is not. Moreover, for the specific issue of using the peak of the GCLF as a standard candle, the overall form of the distribution is unimportant, provided one has a reliable method of locating the peak.

A different approach has been taken by McLaughlin (1994) who notes that the Milky Way GCLF is asymmetric and suggests that the *mode* of GCLFs may provide a more reliable standard candle. The difficulty with this idea is finding a reliable method of locating the mode without the unattractive step of binning the data. An algorithm for such a procedure is currently being developed (Ashman, Conti & Zepf 1995). These considerations suggest to us that while a Gaussian model is not perfect, it is currently as good as any alternative, at least until more data demand a different parametrization of the GCLF.

2.2 Mass Functions

In order to quantify the effects of metallicity variations on the GCLF, we need to have a globular cluster mass function. We derive such a mass function from the 117 globular

clusters in the Milky Way dataset described above. This is achieved by using spectroscopic metallicities for the clusters from Harris (1994) along with their V -band magnitudes. Using Worthey’s (1994) stellar population synthesis models, we use the metallicities to obtain V -band mass-to-light ratios from which we calculate a mass for each cluster.

Note that we are primarily interested in *differences* in $(M/L)_V$ produced by metallicity variations. We have used Worthey’s (1994) models for 12 Gyr stellar populations, but the *form* of the derived mass function is similar if we use the 17 Gyr models. The masses of individual clusters are therefore somewhat uncertain (even for the 12 Gyr models, the $(M/L)_V$ are higher than those inferred from velocity dispersion measurements), but the relative masses and thus the overall shape of the mass distribution is more reliable, at least if Milky Way globular clusters are roughly coeval.

The results of this procedure are summarized in Table 2, where we consider the distribution of the logarithm of globular cluster masses to allow a direct comparison to the GCLF. We have also estimated the mass function of M31 globulars using a similar technique, except that the metallicities are based on $(B - V)$ colors from Reed et al. (1994). To retain clusters without B magnitudes, we assigned them the mean $(B - V)$ color of the dataset. This is clearly less than ideal and will introduce errors into the calculated mass distribution. Nevertheless, as illustrated by Table 2, the two mass functions are indistinguishable. As we argued for the GCLF, the peak and dispersion of the M31 mass distribution is probably biased by the lack of clusters fainter than $M_V = -5.5$. It is also worth noting that, based on the skewness, the M31 logarithmic mass distribution is consistent with Gaussian, while the Milky Way distribution is only marginally inconsistent with a parent Gaussian distribution.

The similarity of the two mass functions is, in some ways, more important than the similarity of the GCLFs. As noted above, the mass distribution is a more physically meaningful quantity. In Section 4 we give further arguments in favor of a universal globular cluster mass function.

3. SHIFTS IN THE GCLF PEAK DUE TO METALLICITY VARIATIONS

Jacoby et al. (1992) found that the GCLF distance estimation method is more accurate than its estimated errors, although it gives distances 13% larger than the surface brightness fluctuations technique. This result has the hallmarks of a systematic effect. In this Section, we investigate the possibility that the higher mean metallicity of the globular cluster systems around ellipticals, relative to the calibrating Milky Way system, is responsible for this offset.

Our starting assumption is that the globular cluster mass function is universal. Using the logarithmic mass function found for the Milky Way globular cluster system in the previous section, we simulate GCLFs by convolving this mass function with a metallicity distribution. That is, each “cluster” has a mass and metallicity drawn from an appropriate parent distribution, so that its luminosity can be calculated from the (M/L) - $[\text{Fe}/\text{H}]$ relationships given by Worthey (1994).

As in the calculation of the Milky Way globular cluster mass function, we use the 12 Gyr stellar population models. Note that this procedure generates GCLFs that are likely to be *more* reliable than the mass function. This is because, in calculating the GCLFs, the physical effect of importance is the variation in mass-to-light ratio due to metallicity. We have already noted that Worthey’s (1994) mass-to-light ratios are rather higher than those observed for globular clusters, and that our choice of using his 12 Gyr models is somewhat arbitrary. However, if we use the same models to generate the GCLFs, these uncertainties effectively cancel out, and our results are only dependent on the ability of the stellar population models to produce accurate *relative* mass-to-light ratios for coeval populations of different metallicities.

When the mass and metallicity distributions are convolved, the resulting dispersion in the GCLFs is primarily due to the dispersion in the mass function. A typical dispersion in the metallicity distribution of globular cluster systems is 0.4 dex or less, roughly corresponding to a dispersion of 0.15 magnitudes in V -band. (The precise value depends on the absolute metallicity since the $(M/L)_V$ - $[\text{Fe}/\text{H}]$ relation is non-linear.) The dispersion of the

logarithmic mass function is 0.5 dex (see Table 2), corresponding to 1.2 magnitudes and is therefore responsible for almost all the dispersion in the GCLF. We checked this explicitly by simulating V -band GCLFs with a single simulated mass function (based on Milky Way parameters) and four sets of 100 simulated metallicity distributions, each with 500 datapoints. The simulations are characterized by a mean metallicity μ and Gaussian dispersion σ . We generated distributions with $(\mu = -1.3, \sigma = 0.2)$, $(\mu = -1.3, \sigma = 0.7)$, $(\mu = -0.4, \sigma = 0.2)$ and $(\mu = -0.4, \sigma = 0.7)$. We found that while the peak of the GCLF varied for the different values of μ as expected, its dispersion remained constant, even between the cases with $\sigma = 0.2$ and $\sigma = 0.7$. Moreover, for the sets with the same μ the GCLF peak was the same for the two different values of σ . This is important since it allows us to use a single characteristic dispersion for the metallicity distribution in our full simulations, rather than having to worry about a range of dispersions.

Our main simulations also involve 500 datapoints for each case, but now we randomly draw points both from a logarithmic mass function and a metallicity distribution. The parent mass function has the Milky Way parameters given in Table 2. For the metallicity distributions we again assumed a Gaussian form, but fixed the dispersion at 0.35 dex for all cases. Based on the results described above, a metallicity distribution with zero dispersion would probably generate equally reliable results, but our approach more closely simulates the observed properties of these systems. The mean of the metallicity distribution was varied from -1.6 dex to -0.2 dex in steps of 0.2 dex, with an additional set of simulations performed for $[\text{Fe}/\text{H}] = -1.35$, the mean metallicity of the Milky Way globular cluster system. This allowed us to calculate GCLFs for a range of metallicities in five photometric bands: B , V , R , I and J . For each mean metallicity, 100 GCLFs were simulated for each band. Each resulting GCLF was fit with a Gaussian and the peak and dispersion were recorded. Thus for each value of metallicity, we obtained 100 values of the GCLF peak and the corresponding dispersion. The distribution of peak values was analyzed using ROSTAT to obtain a mean peak value and 90% bootstrapped confidence limits.

In Figures 2 and 3 and Tables 3 and 4 we present our results. Figure 2 shows the absolute magnitude of the GCLF peak for the range of metallicities described above, whereas Figure 3 shows the offset in the peak relative to the GCLF of the Milky Way globular cluster system. (Note that the Milky Way peak value is obtained from the mean of our simulations, but the B -band and V -band values are consistent with those determined directly in Section 2.) The typical error associated with datapoints in both figures is about 0.11 magnitudes and is dominated by the uncertainty in the peak of the Milky Way mass function (or equivalently, the V -band GCLF from which it is derived). The dispersion in the GCLF peaks for each set of parameter values is small (around 0.02 magnitudes), as is expected for the 500 datapoints of each simulation. The ROSTAT analysis revealed that the distribution of GCLF peak values for a given metallicity and band is itself Gaussian-distributed. Thus for datasets smaller than 100 points, an error of σ/\sqrt{N} should be added in quadrature to the 0.11 magnitudes.

The most striking result apparent from Figures 2 and 3 is that the shift in the GCLF peak in B and V can be substantial. Two recent studies give median globular cluster metallicities of -0.56 dex for NGC 3923 (Zepf et al. 1995) and -0.31 dex for NGC 3311 (Secker et al. 1995). The latter corresponds to a B -band shift of about 0.6 magnitudes relative to the Milky Way. While the globular cluster system of this galaxy is extreme, characteristic metallicities for the globular cluster systems of ellipticals are about 0.5 dex higher than the Milky Way system, corresponding to GCLF peaks that are fainter by about 0.25 magnitudes in B and 0.15 in V . The shifts are sufficient to have an appreciable effect on distances derived using the GCLF method.

4. IMPLICATIONS FOR GCLF DISTANCES

The vast majority of galaxies for which GCLF distances have been obtained are ellipticals. The basic technique involves fitting a Gaussian to the observed GCLF, determining the apparent magnitude of the peak, m_0 , and obtaining a distance modulus by comparing this peak to the absolute magnitude of the GCLF peak in the Milky Way. The details of the procedure are described by Jacoby et al. (1992).

The results of Section 3 illustrate that previous applications of the GCLF method are likely to have overestimated galaxy distances, since in most cases it has been applied to elliptical galaxies with globular cluster systems with higher mean metallicity than the Milky Way system. The error in the derived distance modulus due to this effect is simply the shift in the GCLF peak, ΔM_0 , given in Figure 2 and Table 3. Since the distance is related to the distance modulus by:

$$d = 10^{(0.2(m-M)+1)} \text{ pc}, \quad (4.1)$$

the fractional error in distance produced by an error ΔM_0 in the distance modulus is:

$$\frac{d_1}{d_2} = 10^{0.2\Delta M_0}, \quad (4.2)$$

where d_2 is the true distance and d_1 is the distance obtained by assuming the peak of the observed GCLF has the same absolute magnitude as M_0 in the Milky Way. The percentage error in distance can therefore be written as

$$\epsilon(d) = 100(10^{0.2\Delta M_0} - 1) \% \quad (4.3)$$

where a positive error indicates that the distance has been overestimated.

In Figure 4 we present the percentage error in derived distance as a function of metallicity for the different photometric bands. As noted earlier, most of the galaxies with GCLF distances considered by Jacoby et al. (1992) are ellipticals. The GCLFs of these galaxies were primarily obtained in B -band. Assuming a typical mean metallicity of -0.8 dex for the globular cluster systems of these galaxies (Harris 1991 and references therein), Table 4 gives $\Delta M_{B0} \approx 0.24$ mag. Substituting this value into equation (4.3) we find that this leads to an overestimate in distance of 12%. This compares to the 13% offset found by Jacoby et al. (1992) between GCLF distances and those found using the surface brightness fluctuations technique. We conclude that all of the offset between these two methods of distance estimation can be explained by a shift in the GCLF peak due to metallicity.

4.1 A Case Study: NGC 1399

A detailed reassessment of GCLF distances that takes into account metallicity variations is beyond the scope of the present paper. Ideally, one would correct M_0 in each galaxy based on the observed metallicity of its globular cluster system, but in many cases such metallicities are not available. However, a study of the shift in M_0 in NGC 1399 provides a useful illustration of the effect.

Bridges et al. (1991) studied the GCLF of NGC 1399 in both B and V . They found the peak of the GCLF to occur at $V = 23.75$ and $B = 24.55$ and assumed GCLF peak values in the Milky Way of $M_{V0} = -7.36$ and $M_{B0} = -6.84$. This leads to distance moduli of $(m - M)_0 = 31.2$ (V) and $(m - M)_0 = 31.5$ (B). [Note that these numbers differ slightly from those quoted by Bridges et al. (1991) due to an inconsistency in the reddening used by these authors. We have used $A_B = 0.0$ throughout (Burstein & Heiles 1984) and corrected the above distance moduli accordingly.]

The mean metallicity of the NGC 1399 globular cluster system is $[\text{Fe}/\text{H}] \approx -0.75$ (e.g. Ostrov et al. 1993 and references therein). This leads to a predicted shift in the GCLF peak relative to the Milky Way of $\Delta M_{V0} \approx 0.18$ and $\Delta M_{B0} \approx 0.26$. Using these peak shifts along with the GCLFs of Bridges et al. (1991) and the values for the Milky Way GCLF peaks found in Section 2, we find distance moduli to NGC 1399 of:

$$(m - M)_0 = 31.0 \pm 0.35 \quad (V)$$

$$(m - M)_0 = 30.9 \pm 0.40 \quad (B)$$

where the errors are based on Bridges et al. (1991) estimate of the uncertainties in the derived GCLF peaks. Note that about half the difference in the B -band distance modulus derived here and by Bridges et al. (1991) arises through our fainter value for M_{B0} in the Milky Way.

Ciardullo et al. (1993) find a distance modulus to NGC 1399 of 30.99 ± 0.1 based on the surface brightness fluctuations method. Clearly our result is in excellent agreement with this value.

4.2 A Universal Globular Cluster Mass Function

Secker & Harris (1993) assumed a Virgo distance modulus based on the surface brightness fluctuations scale in order to derive the peak of the GCLF in four Virgo ellipticals. They concluded that the GCLF peak in these ellipticals is fainter than the mean of the Milky Way and M31 peak, with an offset of $\Delta M_{V0} = 0.31 \pm 0.33$. (This is essentially another way of describing the offset between the GCLF and surface brightness fluctuations distance scales.) Secker & Harris (1993) also confirmed the earlier result of Harris et al. (1991) that the scatter in M_{V0} between ellipticals was less than 0.2 magnitudes.

A more recent study by Fleming et al. (1995) provides the important addition of another GCLF of a spiral galaxy (NGC 4565) to the database. The GCLF of NGC 4565 has a peak comparable to the Milky Way and M31 in V -band, adding weight to the evidence for an offset between the GCLFs of spirals and ellipticals. Fleming et al. (1995) quote GCLF peaks of $M_{V0} = -7.4 \pm 0.2$ and $M_{V0} = -7.2 \pm 0.1$ for spirals and ellipticals, respectively, using all current data. Again, our results indicate that this difference can be accounted for entirely by metallicity variations.

Since our simulations assume that the globular cluster mass function is universal, their success in explaining variations in M_0 provide some evidence for such universality. This is a potentially important result, since it suggests that globular cluster masses are independent of both metallicity and environment. Such a finding provides a useful constraint on models of globular cluster formation. It is possible in principle to confirm the universality of the globular cluster mass function, either by measuring globular cluster metallicities along with GCLFs, or obtaining GCLFs in metallicity-insensitive bands.

One possible difference between globular cluster mass functions of spirals and ellipticals is the dispersion. We argued in Section 2 that the lower dispersion in the GCLF (and hence in the mass function) of M31 relative to the Milky Way might be a result of incompleteness. However, various studies have found that the GCLF dispersion for ellipticals is significantly higher than that of spirals (e.g. Harris 1991; Secker & Harris 1993; Fleming et al. 1995). For

a Gaussian fit, the GCLF dispersion is around 1.4 for ellipticals and 1.2 for spirals. Although the dispersion of the globular cluster metallicity distribution is broader for ellipticals than spirals, this is unlikely to be responsible for the observed difference in the GCLFs. As mentioned in Section 2, for realistic metallicity distributions, the dispersion in the GCLF is almost completely dominated by the dispersion in the mass function. The GCLF observations therefore suggest either that the globular cluster mass function is intrinsically broader in ellipticals relative to spirals, or that some other effect is at work. For instance, Fleming et al. (1995) have suggested that in spirals, the disk produces dynamical evolution of the GCLF, reducing its dispersion.

Another possibility is that the globular cluster mass function is constant, and the GCLF dispersion is inflated by age differences among the globular clusters around elliptical galaxies. The bimodal and multimodal color distributions of most elliptical galaxy globular cluster systems (Zepf & Ashman 1993; Zepf et al. 1995 and references therein) suggest that the globulars formed in two or more bursts, possibly as a result of galaxy mergers (Ashman & Zepf 1992). Irrespective of the mechanism, multimodal color distributions suggest there are age differences between the individual populations of globulars. Although a detailed analysis of all possible age and metallicity combinations is beyond the scope of this paper, a preliminary analysis suggests that age is not a promising way to explain the broader dispersion of elliptical galaxy GCLFs. If the age-metallicity combination is fixed to reproduce the observed color distribution, the results tend to be very similar to those found when the color distribution is assumed to reflect only metallicity differences. This is a consequence of the similar effect that age and metallicity have on integrated stellar colors and mass-to-light ratios.

5. CONCLUSIONS

We have investigated the use of the GCLF as an extragalactic distance indicator. The peak of the GCLF can be used as an effective standard candle for distance measurements. However, corrections for metallicity differences between globular cluster systems must be

made since objects of the same mass but different metallicity will have a different luminosity. Based on a series of simulations, we have derived metallicity corrections for a range of photometric bands and metallicities. Metallicity variations typically produce a shift of about 0.25 magnitudes in B -band between ellipticals and the Milky Way. This result is supported by observations of elliptical galaxies which indicate globular clusters of higher mean metallicity and fainter GCLF peaks relative to the Milky Way. Our study shows that the offset between the GCLF and surface brightness fluctuations distance scales can be explained entirely by this metallicity effect.

Our results strengthen the evidence that the globular cluster mass function is remarkably similar in different galaxies, provided our interpretation of the difference in GCLF peaks between galaxies is correct. This work also suggests that the accuracy of the GCLF peak as a distance indicator is improved significantly by either obtaining colors, so that stellar population differences can be explicitly accounted for, or by observing in bands least affected by metallicity variations, such as I or J .

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FIGURE CAPTIONS

Figure 1. The V -band luminosity functions of the globular cluster systems of the Milky Way (left) and M31 (right). The best-fitting Gaussians are also shown. (In the case of the Milky Way, the best fit excludes the 5 faint clusters that are removed by a 3σ clip.)

Figure 2. The absolute magnitude of the peak of the GCLF in five photometric bands plotted against mean globular cluster metallicity. We have used Worthey’s (1994) stellar population synthesis models for a coeval population with an age of 12 Gyr. B , V , R , I and J bands are denoted by solid circles, open circles, open squares, solid triangles and open triangles, respectively. It is assumed that the underlying mass function is universal and has the parameters of the Milky Way distribution.

Figure 3. The shift in magnitude ΔM_0 of the GCLF peak plotted against metallicity. Symbols are the same as those in Figure 2.

Figure 4. The percentage error in estimated distance resulting from the assumption that M_0 is the same for all GCLFs irrespective of metallicity. The error is plotted against mean globular cluster metallicity. Symbols are the same as those in Figure 2.